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RHIC CHALLENGES FOR LOW ENERGY OPERATIONS*

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Abstract

There is significant interest in RHIC heavy ion collisions at $\sqrt{s}$ =5-50 GeV/u, motivated by a search for the QCD phase transition critical point. The lowest energies are well below the nominal RHIC gold injection $\sqrt{s}$ = 19.6 GeV/u. There are several challenges that face RHIC operations in this regime, including longitudinal acceptance, magnet field quality, lattice control, and luminosity monitoring. We report on the status of work to address these challenges, including results from beam tests of low energy RHIC operations with protons and gold.

BACKGROUND AND MOTIVATION

There is significant theoretical and experimental evidence that points to the existence of a QCD phase transition critical point on the QCD phase diagram. If this critical point exists, it should appear on the quark-gluon phase transition boundary in the range of baryo-chemical potential of 100–500 MeV [1]. This corresponds to heavy ion collisions at RHIC with $\sqrt{s}$ =5-50 GeV/u. Experimental identification of this critical point would be a major step towards characterization of QCD at high temperatures and densities.

There is considerable interest in an experimental search of this region using the STAR and PHENIX detectors at RHIC. This data will complement existing fixed-target data from the AGS and SPS. Required integrated luminosities for this search are low but challenging; approximately 5×10^6 events are needed at each of 6–7 energies to improve on existing results by a factor of 2–4 [2, 3].

Fig. 1 shows several scalings for RHIC Au-Au luminosity in the low-energy regime of interest. Above the nominal injection energy of 9.8 GeV/u, the beam size and aperture both scale with γ, so the event rate (or luminosity) scales as γ^2. Here RHIC runs as a ramping collider, and previous collider runs are consistent with prediction, with peak luminosity $L_{\rm peak} = 1.0 \times 10^{25}{\rm cm}^{-2}{\rm s}^{-1}$ at injection energy.

At and below nominal injection energy, RHIC runs as a colliding storage ring, and beam size, field quality, longitudinal acceptance, and IBS growth will conspire to make this scaling worse. It is therefore important to test RHIC low energy performance to determine expected luminosities for long-term program planning. Assuming γ^3 scaling, $L_{\rm peak} \approx 1.2 \times 10^{23}{\rm cm}^{-2}{\rm s}^{-1}$ at $\sqrt{s}$ =5 GeV/u.

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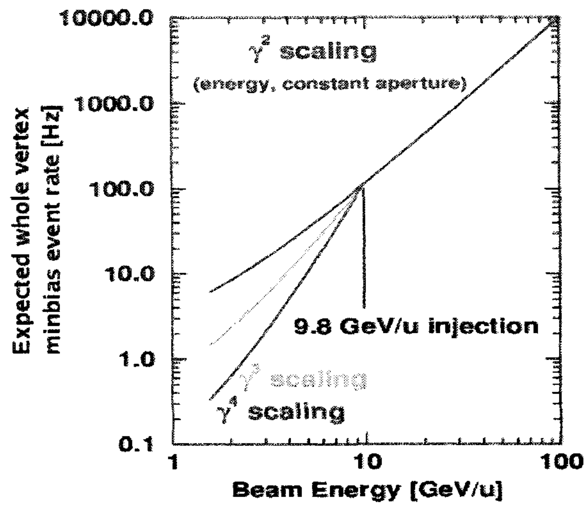

Figure 1: Scaling of RHIC minbias event rate (or luminosity) into the low energy regime. Energies of interest are $\sqrt{s}$ =5-50 GeV/u, or beam kinetic energies of 1.6–24.1 GeV/u. Determination of low energy collision rate scaling with γ is important for RHIC low-energy run planning.

PARAMETERS

Table 1 compares some RHIC parameters that are relevant for low-energy operations, including two test runs that occurred in 2006 with protons and 2007 with gold. Summaries of these test runs are presented in the next two sections of this paper.

For linear field response, power supply current scales with magnet rigidity Bρ. At the lowest requested collision energy, rigidity and power supply currents are only 20% of their values at nominal injection energy. Main power supply regulation has been tested in RHIC at these currents, and shows no problems. Other field quality was experimentally investigated during the 2006 and 2007 test runs.

At low energies, Au beam becomes less relativistic, and the ion beam velocity is lowered out of the RHIC RF tuning range of 27.98–28.17 MHz for the standard RHIC harmonic number $h = 360$. The harmonic number must therefore be raised for collision energies less than $\sqrt{s}$ = 17 GeV/u. RHIC is three-fold symmetric, so only harmonic numbers divisible by 3 can produce simultaneous collisions at both STAR and PHENIX experiments.

Longitudinal and transverse acceptance vs emittance is another challenge at low energies. RHIC Au beam typically has a longitudinal emittance of 0.2 eV-s/u at injec-

Table 1: Parameters for nominal RHIC Au injection, 2006 and 2007 low-energy test runs with protons and gold, and the lowest energy of interest for the QCD critical point search. Beam sizes are calculated assuming ϵ_N(Au)=40π μm, ϵ_N(p)=10π μm, $\beta^\star$=10m, and β_{max}=170m. L_{peak} assumes γ^3 scaling below nominal injection energy and $\beta^\star$=10m.

Species	$\sqrt{s}$ [GeV/u]	KE_{beam} [GeV/u]	γ	Bρ [T-m]	I_{dipole} [A]	f_{rev} [kHz]	h	$\sigma^*_{95\%}$ [mm]	$\sigma_{max,95\%}$ [mm]	L_{peak} 10^{23} cm^{-2}s^{-1}
Au (inj)	23.47	10.80	12.6	97.3	566.5	77.95	360	2.3	9.5	400
p (2006)	22.5	10.31	11.99	37.4	217.7	77.92	360	1.2	4.9	
Au (2007)	9.18	3.66	4.93	37.4	217.7	76.57	366	3.7	15.3	7.2
Au (low)	5.0	1.57	2.68	19.3	112.4	72.57	387	5.2	21.3	1.2

tion. This beam barely fits into the RHIC bucket RF with 500 kV at $\sqrt{s}$ = 9 GeV/u. At $\sqrt{s}$ = 5 GeV/u longitudinal acceptance is only 0.12 eV-s/u, and 10–20% of the beam immediately debunches even with perfect longitudinal injection. Transverse acceptance issues in the transfer line provide similar limitations, leading to expectations of only 20–50% injection efficiency at the lowest energy.

2006 PROTON TEST RUN

The first 24-hour test of RHIC at low energy occurred June 5–6 2006, during the 2006 RHIC polarized proton run. As Au beam was not available, the objective of this run was to evaluate setup time, power supply behavior, linear field quality, beam stability, and optics. RHIC $B\rho$ was 37.4 T-m, corresponding to beam kinetic energy of 10.31 GeV, less than half of the nominal proton injection kinetic energy of 22.87 GeV. This rigidity was chosen because it corresponds to a potentially interesting feature in the QCD phase diagram[3]; it is also about halfway between nominal injection and the lowest energy of interest. Protons are still highly relativistic at this energy, so the RHIC harmonic number was unchanged.

After initial setup, first circulating beam was achieved in approximately 3 hours in both rings; another 3 hours were taken for RF setup and capture. Injection efficiencies were 70–80%, with beam lifetimes of 5–10 hours at the normal polarized proton working point. Vernier scan suffered from lack of clean luminosity signal and high backgrounds.

Optics measurements were performed using difference orbits and orbit response matrices. These measurements indicated 10-15% beta waves in both planes compared to the design injection model, consistent with optics quality at nominal injection field in RHIC. This combined with excellent beam lifetimes indicated that field quality at these energies was not problematic. Beam ripple was also measured, and showed no deviation from nominal injection spectra; power supply ripple and regulation at this energy is therefore also not an issue.

Low-field extrapolation of RHIC magnet measurements shows that the RHIC main dipole sextupole component nearly doubles from -9 units to -16 units from nominal injection to this energy. This created additional chromaticity that was not fully compensated with the existing configuration of RHIC sextupoles. Vertical chromaticities could only be set to about +1–+2 below transition energy; instabilities were damped with strong octupoles, though beams continued to be metastable. For physics runs at this and lower energy, defocusing sextupole power supplies will be reversed to allow proper chromaticity control.

2007 GOLD TEST RUN

The second 24-hour test of RHIC at low energy occurred June 6–7 2007, during the 2007 RHIC Au-Au run. RHIC $B\rho$ was 37.4 T-m, the same as the proton test run, to leverage previous setup. This corresponds to an Au beam kinetic energy of 3.66 GeV/u. The objectives of this run were to use a new RHIC harmonic number, evaluate Au transverse and longitudinal acceptance, and measure Au-Au luminosity to place a measured low-energy point on Fig. 1. A $\beta^\star$ = 10 m lattice maximized transverse aperture.

h = 366 setup was straightforward for RHIC RF and AGS to RHIC synchro. The RHIC beam synchronous event system also relies on an RF clock to generate experiment trigger clocks and other beam-synchronous RHIC instrumentation timing [4]. Event generator hardware that generates its own h = 360 revolution fiducial event was bypassed and the beam synchronous links were reconfigured, but at the cost of priority of the fiducial event on the link. PHENIX could not lock to this clock, but STAR could, with trigger resets every few minutes.

Fig. 2 shows Au beam lifetime for three consecutive

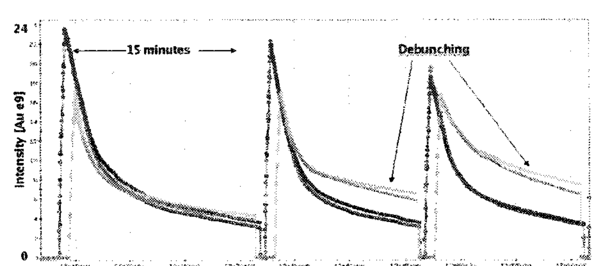

Figure 2: Au beam lifetime at $\sqrt{s}$ = 9.18 GeV/u (blue and yellow rings), with a slow exponential decay component of 20 minutes and a fast exponential decay component of 2 minutes. Bunched and total beam currents are displayed; debunching is clearly visible, so momentum aperture is larger than the RF bucket size.

stores during this low-energy run. Injection efficiencies were 80-90%. Decomposition of the beam lifetime shows two main exponential components: a slow component of 20 minutes, and a fast component of 2 minutes. The slow component is consistent with an IBS growth time prediction at this energy. Measured $\epsilon_{N,x,y} = 15 - 25\ \pi\ \mu$m. Longitudinal injection efficiency was 100%; estimated longitudinal emittance was 0.14 eV-s/u, significantly smaller than the expected 0.2 eV-s/u, perhaps because AGS transition crossing was unnecessary.

Four vernier scans were taken at the STAR experiment. Unfortunately none could be taken with new PHENIX detectors due to trigger clock problems. Fig. 3 shows a STAR vernier scan over ± 9 mm in 15 minutes in both planes. Beams were longitudinally cogged out of collision early in the store, demonstrating only 5% backgrounds. Fig. 4 shows normalized STAR beam-beam counter (BBC) event rates during a horizontal vernier scan; the beam width of 4 mm is consistent with an average normalized horizontal emittance of 25 $\pi\ \mu$m.

FUTURE PLANS

At the lowest energies, RHIC low energy operation is clearly constrained by longitudinal and transverse acceptance. AGS electron cooling would reduce these constraints. Simulations indicate that an AGS electron cooler at AGS injection energy would reduce gold beam longitudinal emittance by a factor of 10, improve peak luminosity by a factor of 100, and provide an increased integrated luminosity of a factor of 30–100 to the RHIC low-energy program. This cooler requires a cooling section length of 1.5m, solenoidal field of 0.1 T, electron energy of 50 keV, and electron current of 0.5A. These parameters are easily achievable with existing technology and expertise, but IBS and space charge limitations require careful study.

A test of gold collisions at $\sqrt{s} = 5$ GeV/u has been proposed for the 2008 RHIC run to determine luminosity and luminosity lifetime, and to evaluate requirements for potential AGS electron cooling. Injection efficiency of 20–50% and IBS lifetimes of a few minutes are expected, so vernier scans and luminosity measurement will be challenging. Beam synchronous clock issues for harmonic numbers other than 360 will be resolved during the 2007 shutdown, and tested with experiment triggers.

CONCLUSIONS

RHIC heavy ion collisions at $\sqrt{s}$ =5-50 GeV/u are motivated by a search for the QCD phase transition critical point. Two test runs, with protons in 2006 and gold in 2007, have demonstrated program feasibility at $\sqrt{s} = 9.18$ GeV/u, and gold beam parameters are better than expected. RHIC harmonic number changes pose no problems to RF; there are minor problems with hardware clocks that will be fixed during the 2007 summer shutdown. AGS electron cooling is being studied as a possible upgrade path to improve low-energy performance.

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REFERENCES

[1] M. Stephanov, K. Rajagopal, and E. Shuryak, "Signatures of the Tricritical Point in QCD", Phys. Rev. Lett. **81**, 4816–4819 (1998).

[2] RIKEN workshop proceedings, "Can We Discover the QCD Critical Point at RHIC", March 9–10 2006, `http://www.bnl.gov/riken/QCDRhic/`.

[3] G.S.F. Stephans, "critRHIC: the RHIC low energy program", J. Phys. G: Nucl. Part. Phys. **32** (2006) S447-S453.

[4] H. Hartmann and T. Kerner, "RHIC Beam Synchronous Trigger Module", PAC 1999, pp. 696-9.

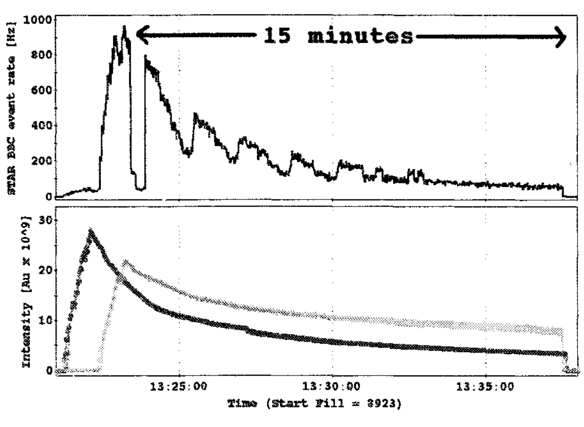

Figure 3: A 15-minute Au-Au store at $\sqrt{s} = 9.18$ GeV/u, showing blue and yellow beam intensities and STAR BBC counter collision rates. Beams were uncogged and recogged at the start of the store; vernier scans in both planes were performed during the store.

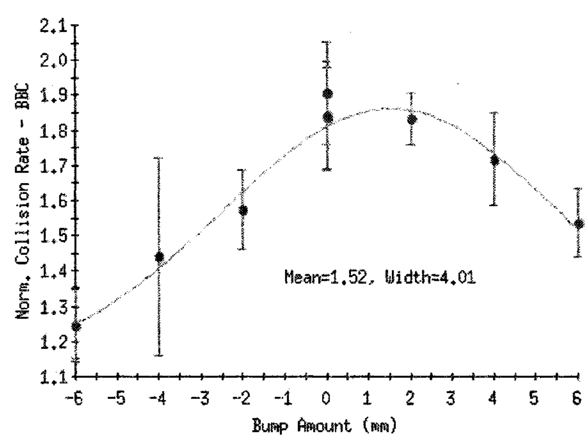

Figure 4: A STAR BBC vernier scan at $\sqrt{s} = 9.18$ GeV/u, scanning beam horizontally over ± 6 mm. There was little background contamination, in contrast to the 2006 proton test run.